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衝撃波現象の定量的可視化に関する研究

著者	水書 稔治
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	みず　かき　とし　はる
氏　　　　　名	水　書　稔　治
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指　導　教　官	東北大学教授　高山　和喜
論文審査委員	主査　東北大学教授　高山　和喜　　東北大学教授　福西　祐 東北大学教授　井小萩　利明 東北大学助教授　Harald Kleine

ABSTRACT

In shock wave research, quantitative measurement of weak shock waves is one of the most important experimental techniques. The recent development of holographic interferometry and also the advancement of computer aided image data processed enabled digital phase shift holographic interferometry (DPSHI) which has been developed to measure steady phenomena to apply to the quantitative visualization of weak shock wave phenomena. This thesis describes for the first time a successful result of application of DPSHI to the quantitative measurement of weak shock wave phenomena.

In Chapter 1, the background of the present research is described.

In Chapter 2, as a preparation for the generation of weak shock waves, the explosion of silver azide pellets weighing 10 mg was studied experimentally and numerically. The explosive pellets were ignited by the irradiation of pulsed Nd:YAG laser beam of 7 ns pulse duration. The shape of the explosive pellets was 1.5mm in diameter and 1.5 mm in length and have purity of 99%. At first, the minimum laser energy with which the detonation was initiated was measured by means of two methods. Pulsed laser beams were successively attenuated by passing through neutral density filters and irradiated on the pellet surface. The value of laser energy was determined at which the ignition was incompleted by the irradiation. Another method was also tried in which the pulsed laser beam at given beam diameter was diverged by passing through a concave lens so as to decrease the intensity. Eventually these examinations gave nearly the same value of minimum ignition energy and was found to be 3.57 ± 0.14 mJ/cm2. Hence, the minimum energy at which the silver azide pellet started to detonate 64 μJ.

The delay time of the ignition of silver-azide pellets was investigated by monitoring the arrival of resulting shock waves and also by the visualization of ignitions using double exposure holographic interferometry. It was eventually found that the ignition delay time could not be distinctively identified and then it would be not longer than 7 ns, the pulse duration of ignition laser beams. It is important to pre-determine the TNT-equivarence ratio of silver-azide pellet, as these micro-explosion is used to scale large scale field explosions. Overpressures of

micro-blast waves of silver azide pellet explosion were systematically measured at various stand-off distances and by changing the amount of silver azide pellets from 0.5 to 10mg. The data so far collected were plotted in overpressrue-scaled distance plane. The comparison of the plots with TNT overpressure curve revealed that the TNT-equivalence ratio was approximate 40%, whereas theoretical TNT equivalence ratio of silver-azide was 42%. This implies that micro-explosion of 10 mg silver azide pellets will be useful for a reliable source of weak shock generation.

In Chapter 3, early stages of silver-azide pellet ignition by the irradiation of pulsed ND:YAG laser was quantitatively investigated. As in particular the shape of shock waves at very early stages was strongly affected by the orientation of cylindrical pellets and also the point on which the laser beam irradiated. In order to identify the early shock shapes, direction indicating color schlieren method was applied, in which the delicate variation of hue corresponds to the direction of density gradient in the test field. Cylindrical pellets were ignited either by direct irradiation of laser beam in air or by attachment on an optical fiber through which pulse laser beam was irradiated. The optimized orientation of the beam irradiation and also the direction of observations were very precisely determined. The effect of the pellet shape on shock wave formation was investigated numerically. In the series of experiments, 0.5 mg silver-azide pellets having slightly irregular shape were ignited again by the laser beam irradiation through the optical fiber and the motion of shock waves were visualize by schlieren method with IMACON468 high-speed camera. Numerical comparison was carried out using AUTODYN-2D and the result agreed reasonably well with the result of visualizations. Very minute structures of jet formation from micro-explosives and induced shock wave were resolved. It is concluded that it is inevitable to generate perfectly spherical shock waves by laser ignition of 10 mg silver azide pellets but it can be achieved at about 200 μs after the ignition and for the production of weak shock waves this method has higher degree of reproducibility and is very reliable.

In Chapter 4, digital phase shift holographic intereromety (DPSHI) that was based on double exposure holographic interferometry and was a relatively easy extension of its optics, was applied for quantitative visualization of shock waves whose shock Mach number is very close to unity. Traditionally DPSHI has been developed mainly for the precise measurement for steady phenomena such as micro-deformation and micro-displacement and thermal convection etc. This technique basically consists of two system of the record of events and the reconstruction and imaging the recorded image data. Its recording system are almost identical to double exposure holographic interferometry except that a mirror of reference beam facing to holographic film has to be tilted during the double two exposure. The process of image reconstruction of DPSHI , however, consists of Michelson interferometry (MI) and a plane mirror which was mounted on piezo device (PZT). MI can reproduce two reference beams which are tilted by small angle each other. This optical setup is identical in the recording system and PZT is a phase-shifter to one of the reference beams of the reconstruction optical setup, which gives a light-path difference by moving the mirror in fractions of laser wavelength. PZT is shifted in a controlled fashion to created the phase angles of 120 and 240 degrees of the reference beam.

By these arrangements three reconstructed images were taken out of a single hologram recorded by DPSHI. The reconstructed image were recorded with a charge-coupled-device (CCD) camera, and stored as digital (256 gray scale) data on a computer. After storing reconstructed image data these were processed numerically by using the Carre method in order to generate the phase map of recorded events. It should be emphasized that unlike the previous studies of DPSHI, the present research successfully extended DPSHI to strongly unsteady phenomena that had very minute density variations. Weak shock waves that was generated by the explosion of 0.5mg silver azide pellet was evaluated by means of DPSHI. The overpressure so far created was 3.1kPa, equivalence to that of shock Mach number 1.007. DPSHI successfully visualized this density variation and the structure of weak shock wave.

In Chapter 5, applications of DPSHI to two unsteady phenomena are demonstrated, such as shock wave motion in a complex geometry, and high-speed but low amplitude liquid motion in a liquid filled small cell. DPSHI successfully detected variations in density in these unsteady phenomena. The first case was related to a topic which experimentally simulated wave motions in a simplified exhaust muffler for automobile engine. Wave motions in a prxyglass box of 200 mm x 1500 mm x 500 mm connected with tubes were visualized by DPSHI. Wave motions were again generated by means of the detonation of 10 mg silver azide pellets. Complex shock wave motions were well identified whose motion could be readily extended to interpolate the wave motion in an engine muffler. At the end of this muffler model, a pressure transducer was installed to ensure the strength of shock waves. Hence, the shock wave visualized in this case was that of Mach number 1.014, whereas Mach numbers of shock waves which were possibly generated by prototype automobile engines for automobiles were reportedly 1.09. Hence the resolution of this application will be good enough to be applied to the weak shock wave research.

In the second example, DPSHI observation was directed to the density measurement in a water filled 7.8mm i.d. and 38 mm long cell. One of the end walls was equipped with piezo actuator (PZT) oscillating at 20 kHz and the other wall had a very small hole in the center. The oscillation of actuator generated 20 kHz pressure waves traveling between the two end walls. Pressure fractuation in the cell was measured by a pressure transducer place on another end wall. DPSHI observations were conducted at three different instants of pressure transmission in the cell: At the moment when the pressure was a maximum; mean value; and a minimum. DPSHI clearly detected the density fluctuations corresponding to the propagation of pressure waves.
at every condition.

In conclusions, a new technique for quantitative visualization of weak shock waves and related phenomena has been developed by introducing a digital phase shift holographic interferometry (DPSHI). The results so far obtained are summarized:

(1) Silver-azide pellets ignited by Nd:YAG laser successfully produced weak shock waves with high degree of reproducibility. This method became very reliable as minimum energy of ignition and optimized orientation for ignition were quantitatively identified.

(2) the TNT equivalence ratio of silver-azide is approximate 0.4.

(3) DPSHI was for the first time applied successfully to unsteady shock wave phenomena. The pressure field of weak shock waves whose overpressure was equivalent to 130 dB was quantitatively visualized.

(4) For various industrial applications of weak shock waves such as wave motions in automobile engine mufflers,DPSHI is only possible fine method to detect minute wave motions accompanying very small density variations. Wave motions in a water filled cell oscillated by piezo actuator were also detected by DPSHI.

審査結果の要旨

衝撃波工学および計測工学の分野では、衝撃波とその背後の状態あるいは非常に非定常性の強い現象を光学可視化で定量的に計測することは重要な研究課題となっている。一方、パルスレーザーを光源とする二重露光ホログラフィー干渉計法は衝撃波現象の定量的計測の有力手段となって久しいが、弱い衝撃波の伝播、回折、収束現象および複雑な境界を過ぎる衝撃波現象の定量計測への応用には、なお、多くの未解決の問題を残している。本論文は、衝撃波現象の定量光学可視化計測に関する研究の成果をとりまとめたもので、全編6章からなる。

第1章は緒論である。

第2章では、微小アジ化銀ペレットにパルスレーザー光照射で起爆して発生した球状衝撃波の特性、起爆に要するパルスNd:YAG レーザー光の最小エネルギーおよび微小アジ化銀のTNT換算係数を求め、大規模爆発と微小爆発との間に相似則が成り立つことを明らかにしている。これは新しい知見である。

第3章では、微小アジ化銀のレーザー光起爆で発生するレーザー光の照射位置および可視化方向を方向指標型カラーシュリーレン法の観察によって最適化することに成功し、次章に用いる検定された球状衝撃波の発生法を確立している。

第4章では、従来定常現象の計測に用いられている位相変位ホログラフィー法を、衝撃波現象あるいは高速現象の計測に適合させるようにデジタル位相変位ホログラフィー干渉計に発展させ、特に、球状衝撃波背後で音圧 130dB に相当する弱い二次衝撃波の定量計測に成功している。これは衝撃波実験に新しい手法を与え、有用な成果である。

第5章では、デジタル位相変位ホログラフィー干渉計法の応用として、自動車エンジン消音器内の波動計測および微小な閉じた円筒形状の水容器内の一端を磁歪振動子で加振したとき容器内に現れる波動と微妙な密度変化の計測に成功している。これはこの計測法が今後多くの現象の計測に適応できることを示し評価に値する成果である。

第6章は結論である。

以上要するに本論文は、衝撃波現象の新しい定量的光学可視化計測法の確立を目指し、デジタル位相変位ホログラフィー干渉計を発展させ、検定された球状衝撃波の発生と伝播過程の計測に適用してその有効性を実証し、さらに弱い衝撃波現象の計測に最適なことを明らかにしたもので、衝撃波工学および計測工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。